PHILIPP AGRIC SCIENTIST
Vol. 107 No. 3, 286-301
September 2024

ISSN 0031-7454

Research Note

Effects of Soil Type, Irrigation Method, and Biomass Application on Grain Yield and Its Determinants in Irrigated Lowland Rice of Agusan

Jehru C. Magahud

DA-PhilRice Agusan, Remedios T. Romualdez, 8611 Agusan del Norte, Philippines

*Author for correspondence; Email: jcmagahud@gmail.com; Tel. No.: +63 918 733 9869

Received: February 08, 2023 / Revised: July 17, 2024 / Accepted: August 05, 2024

Information about the influence of soil type, irrigation method, and biomass use on rice productivity in Agusan is insufficient, despite their importance in developing or improving irrigated lowland rice production. Hence, this study determined the influence of these factors on grain yield and yield-contributing crop traits. It also explained grain yield based on yield determinants and recommended water management for improving grain yield. The greenhouse experiment was laid out in a three-factor randomized complete block design with 10 replications. The treatments were [a] Butuan sandy loam soil (SLS) and Butuan loam soil (LS); [b] continuously flooded (CF) and controlled irrigation (CI); and [c] applied and unapplied biomass. Data on grain yield and yield determinants were gathered weekly, during harvesting, and after harvesting. Relative to LS, SLS had a statistically greater grain output owing to its higher root and water permeability and better balance among soil nutrients, leading to closer-to-the-optimum soil nutrient uptakes and better yield-contributing crop traits. Compared with CI, CF had a statistically superior grain output as it induced the crop to produce more robust tillers, leading to significantly better yield-contributing crop characteristics. Biomass application modified the soil type x irrigation method interaction since the degree at which CF was exhibiting higher grain yield than CI was significantly greater in SLS than LS for experimental units or pots applied with biomass. Moreover, the level at which CF was attaining greater grain yield than CI was statistically similar in SLS and LS for pots unapplied with biomass. It is therefore recommended that rice be grown in Butuan sandy loam instead of Butuan loam, and that CF instead of CI be used in soil with a mild zinc deficiency or sufficient zinc status.

Keywords: Agusan, biomass application, Butuan soil series, continuous flooding, grain yield, irrigated lowland rice

INTRODUCTION

Supplying essential growth factors in the right amounts and time allows rice cultivars to reach their maximum yield potential (Dobermann and Fairhurst 2000; DA-PhilRice 2022). These growth factors are sunlight, carbon dioxide, water, and other soil nutrients. In a given rice variety and weather condition, the amounts and time by which water and other soil nutrients are absorbed by rice plants depend solely and interactively on the soil characteristics, the irrigation method employed, and the fertilizer inputs applied.

The 10-yr (2014 – 2023) production in Agusan's rice fields ranged at 2.94 – 3.64 t ha^{-1}. This production was lower by 0.49 – 1.10 t ha^{-1} than the Philippines' figures, which ranged at 3.43 – 4.74 t ha^{-1} (PhilRice-SED 2024). Frequent rains, poor soil drainage, deficient soil nutrients, and incorrect soil nutrient management limit rice growth and output in Agusan.

Butuan soil series, the major lowland rice soil in the Caraga Region, was formed from the Agusan River's older terraces. Butuan loam covers 74 010 ha in Agusan, while Butuan clay spans 4 688 ha in Surigao. The other lowland soils in Caraga Region are Kitcharao, Anao-aon, and Mambutay soil series, which span a total of 30 269 ha (Carating et al. 2014).

No field studies on differences in rice productivity and productivity contributors in Butuan loam have been done.

This can uncover the characteristics of this important soil type, which can be used in either developing or improving integrated crop management (ICM). Past experiments had simultaneously assessed grain yield in various Agusan locations; however, they did not associate grain yield with the variability of soil characteristics (e.g., soil series, soil texture, etc.) in these locations. Their focus was to compare different nutrient and pest management practices (Burdeos and Batay-an 2012; Soledad and Varquez 2013a; Buresh et al. 2015 ; Agting et al. 2017), and varieties (Soledad and Varquez 2013b; Amas et al. 2017). Furthermore, no field experiments on differences in rice productivity in Butuan soil series and other lowland soil series in the Caraga Region were conducted.

The usual practice of Agusan farmers is to inundate their farms by keeping the irrigation and drainage canals open. Two greenhouse studies using Agusan soil (Butuan series) noted and explained the yield and growth differences of rice under continuously flooded (CF) vs. controlled irrigation (CI). Statistically superior grain output was reported in CF owing to greater soil nitrogen (N) availability (Magahud et al. 2019) leading to better yield-contributing attributes (Magahud and Padios 2022). Such attributes were a statistically longer vegetative phase, higher straw weight and leaf chlorophyll status (Magahud et al. 2019), and a superior leaf health condition during reproductive and ripening stages (Magahud and Padios 2022). It was also reported that the fewer thin, ineffective tillers in CF induced the utilization of more photosynthates and nutrients for boosting the health of the robust, effective tillers (Magahud and Padios 2022).

Controlled irrigation or alternate wetting and drying is an important part of the PalayCheck® system—the country's main platform for developing, learning, checking, and sharing the best rice farming practices (DA-PhilRice 2022). As such, the suitability of CI in Agusan should be carefully studied as a component of a localized PalayCheck® system.

Most Agusan farmers do not apply organic fertilizers; rice straw is scattered on their fields during mechanical harvesting and incorporated into the soil during land preparation. This practice returns the nutrients in the straw back into the soil at the rate of 7.0 kg N, 1.0 kg P, 14.5 kg K, and 0.8 kg S for every ton of grain output (Dobermann and Fairhurst 2000). Yield responses to various proportions of synthetic and organic fertilizers were studied in Agusan rice fields. Grain yields were highest in plots applied with pure synthetic fertilizers, followed by those applied with 50% organic plus 50% synthetic fertilizers, and lastly by those applied with pure organic fertilizers (Sobrevilla and Mabayag 2013a; Rollon et al. 2021; Troza et al. 2021). However, applying organic fertilizers plus urea resulted in a higher yield than applying synthetic fertilizers at rates lower than the soil test-based recommendation (Rollon et al. 2021). Moreover, comparable yields were seen between pure organic and no fertilizer applications (Sobrevilla and Mabayag 2013b; Rollon et al. 2021) and among plots applied with poultry litter, rice straw, sawdust, and wood chips (Ortiz and Estoy 2013).

Owing to the surging prices of commercial synthetic fertilizers, the combined application of synthetic and organic fertilizers is being promoted by the Department of Agriculture in the country's rice-growing areas (Gomez 2022; Satuito and Valenzuela 2022), including Caraga Region (Barcena 2022; DA Caraga 2022). The promotional messages include reducing the use of synthetic fertilizers, incorporating rice straw into the soil, and applying organic fertilizers. The deficiency in soil nutrients due to reduced synthetic fertilizer rates will be satisfied by the organic fertilizers applied. In support of this campaign, more location-specific experiments to explain the positive effects of using both kinds of fertilizers are needed.

No studies on the interactions of soil type, irrigation method, and biomass application on grain yields of rice in Agusan have been conducted despite the importance of knowing these interactions to effectively craft a location-specific package of technologies for the province. Hence, this study aimed to assess the effects of soil type, irrigation method, and biomass application on grain yield and yield-contributing plant traits of PSB Rc18 grown in Agusan.

MATERIALS AND METHODS

Experimental Treatments, Characteristics of Soil or Growth Media, and Crop Establishment and Maintenance

The three factors of the experiment were soil type, irrigation method, and biomass application.

Bulk soils were collected from two adjacent rice farms (9.067852°N, 125.588326°E; and 09.066603°N, 125.584215°E) in Remedios T. Romualdez, Agusan del Norte, Philippines. The farms are rice production areas in PhilRice Agusan, where rice straws are seasonally scattered during mechanical harvesting and incorporated into the soil during land preparation. Soil profile descriptions were done in these two rice farms in May–June 2018 and were identified as the Butuan series because the soils were underlain by clay with yellow mottles (Carating et al. 2014).

The bulk soils were derived from the plowed or 0 – 25 cm depths after final leveling but before rice planting in June and July 2018. Air-dried soil samples were submitted to Central Mindanao University for chemical laboratory analyses using standard methods of PCAARRD (1980). The following were the specific procedures followed: (1) potentionmetric method using a 1:5 soil:water ratio for soil pH, (2) Walkley-Black method for organic matter (%), (3) modified Kjeldhal method for total nitrogen (N) (%), (4) Bray-2 method for extractable phosphorus (P) (mg kg^{-1}), (5) ammonium acetate extraction followed by distillation and titration for cation exchange capacity (cmol$_c$ kg

Table 1. Properties of soil series and their qualitative descriptions

Soil type	pH	Organic matter, %*	Total nitrogen, %	Extractable phosphorus, mg kg^{-1**}	Cation exchange capacity (CEC), cmol$_c$ kg soil^{-1}	Exchangeable cations, cmol$_c$ kg^{-1**}			(Ca+Mg):K ratio	Extractable zinc, mg kg^{-1**}	Sand-silt-clay %	Soil Textural Class	Water Holding Capacity, %
						Potassium (K)	Calcium (Ca)	Magnesium (Mg)					
Butuan sandy loam	6.87	3.59, highly suitable	0.26	7.53, deficient	44.47	0.308, medium	2.84, sufficient	25.88, sufficient	93:01:00	below detection level	54-30-16	sandy loam	61.20
Butuan loam	6.95	4.75, highly suitable	0.28	6.91, deficient	41.75	0.315, medium	2.90, sufficient	27.87, sufficient	98:01:00	2.53, sufficient	50-36-14	loam	59.03

soil^{-1}), (6) ammonium acetate extraction and analysis of element concentration via flame photometer for exchangeable potassium (K) (cmol$_c$ kg soil^{-1}), (7) ammonium acetate extraction and analysis of element concentration via atomic absorption spectrophotometer for exchangeable calcium (Ca) and magnesium (Mg) (cmol$_c$ kg soil^{-1}), (8) diethylenetriaminepentaacetic acid extraction and analysis of element concentration via atomic absorption spectrophotometer for extractable zinc (Zn) (mg kg^{-1}), (9) hydrometer method for soil texture, and (10) "core" method for water holding capacity (%). The properties of soil samples and the qualitative descriptions of their suitability for irrigated lowland rice production are shown in **Table 1.** Based on their soil textures, the soil types tested in this study were Butuan sandy loam and Butuan loam.

A nutrient omission pot experiment (Descalsota et al. 2002) was conducted from August 15 to October 12, 2018. The collected soils were transferred into seven pots representing one complete and six minus-one element treatments. The ready-to-use fertilizer formulations in a kit, brought from the Philippine Rice Research Institute, were mixed into the potted soils. Rice was then planted and grown in the pots until maximum tillering stage. An element was considered insufficient if the tiller count and shoot weight data in a particular minus-one element pot were < 80% than those in the complete-element pot, while an element was adequate if the same data were > 80% than those in the complete-element pot. Tiller count and shoot weight data showed that soil N, K, and Zn were insufficient while P, sulfur (S), and copper (Cu) were adequate in the sandy loam soil. Soil N and K were also insufficient while P, S, Cu, and Zn were adequate in the loam soil (Fig. 1).

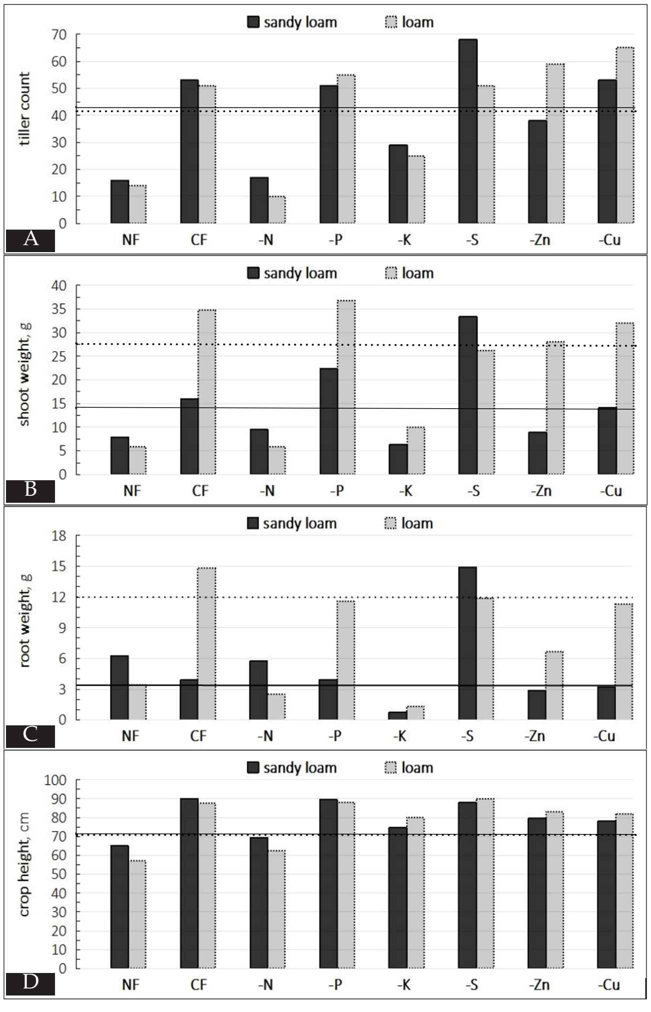

Fig. 1. Comparisons for tiller counts (A), dry shoot and root weights (B, C), and crop height (D) during harvest of rice grown in sandy loam vs. loam soil in no fertilizer (NF), complete fertilizer (CF), minus nitrogen (-N), minus phosphorus (-P), minus potassium (-K), minus sulfur (-S), minus zinc (-Zn), and minus copper (-Cu) treatments; bars above horizontal lines indicate nutrient sufficiency, bars below horizontal lines indicate deficiency.

This study was done in PhilRice Agusan's greenhouse from August 15 to November 23, 2018. Conditions in the greenhouse were easily controlled, enabling the researchers to efficiently employ the experimental treatments. Eight kg of homogenized soil was transferred into black plastic pots (23-cm height, 27-cm top diameter, and 20-cm bottom diameter). The collected bulk soils or plant growth media were added with irrigation water to manually disaggregate soil particles, mixed thoroughly, and passed through a fine mesh to remove undecomposed plant materials. Each pot was planted with five 12-d-old rice seedlings. Each pot was thinned when seedlings were fully established, the two healthiest of which were retained. Fertilizer application for each pot was based on the 74-28-43-24 kg N-P$_2$O$_5$-K$_2$O-S/ha fertilizer rate (PhilRice 2007; Magahud et al. 2019), assuming below-critical leaf color chart (LCC) values at mid-tillering and early panicle initiation stages. Such a rate is equivalent to the following fertilizers applied in every pot: 0.80 g 14-14-14-12S and 0.10 g 0-0-60 at the early stage (7 d after transplanting [DAT]) plus 0.20 g urea each at mid-tillering (36 DAT) and early panicle initiation (48 DAT). Urea application was based on weekly LCC values.

For biomass application, the two treatments employed were applied biomass (alternative practice) and unapplied biomass (conventional practice). The biomass used were rice roots from a previous greenhouse experiment, which were pulverized, passed through a fine mesh, and mixed thoroughly. Two grams of the prepared biomass was applied and thoroughly mixed into the soil of each pot 1 d before planting; this represents the field application rate at 10 bags of plant or rice biomass per hectare (DA IV-CALABARZON 2022) based on the following computations:

10 bags biomass/ha x 50 kg biomass/1 bag biomass = 500 kg or 500,000 g biomass ha^{-1}

500,000 g biomass/ha x 1 ha/250,000 rice hills[†] = 2 g biomass per rice hill or pot

[†]DA-PhilRice (2022)

PSB Rc 18, a variety suitable for the area, was planted. It is one of the more popular rice varieties usually grown in Caraga. In some areas of Surigao, which are adjacent to Agusan, PSB Rc 18 is the most preferred and grown rice variety.

The two irrigation methods—continuously flooded (CF) and controlled irrigation (CI)—were done using the procedures of Magahud and Padios (2022) and Magahud et al. (2019). CF is the conventional practice, while CI is the alternative practice. The greenhouse's roof was made of transparent plastic to prevent rainwater from the pots.

The rice plants in this greenhouse study were grown in the same soil and exposed to the same water management as those in the Agusan field. However, since rice plants are grown in a greenhouse made of net and plastic materials, the climatic factors such as sunlight, temperature, and humidity, and other field factors which would require a different water and chemical management such as the presence of golden apple snails and insect pests were not reflected in this greenhouse study. The term "Agusan" was included in this study's title to indicate that the results on soil type, irrigation method, and biomass application are specifically for Agusan conditions.

Gathering of Data on Grain Yield and its Determinants

Greenness levels (LCC values) of the tallest leaf in every pot were determined qualitatively using the 4-panel leaf color chart (DA-PhilRice 2022). Measurements were done every week at 8:00 – 9:15 AM for 14 – 98 d after planting (DAP).

Tillers were counted weekly at 19 – 96 DAP. A tiller bud was considered as an individual tiller if its leaf sheath and blades had grown separately from its mother tiller, and if its leaf sheath was fleshy or filled with photosynthates. Green, dotted, and dried leaf counts were gathered for the whole plant in every pot at 14 – 98 DAP. Green leaves are the young ones found at the top of the rice plant, with < 50% of their surface area covered with dots. Dotted leaves are older than the green leaves located at the mid-portion of the rice plant; they are yellowish in color, with at least 50% of their surface area covered with dots. The dots are brown in color and signify withering or senescence of the leaves. Dried leaves are the oldest ones at the base of the rice plants; they are withered and fully covered with dots. Green, dotted, and dried leaf percentages were also computed.

The durations from planting to panicle emergence, anthesis, and spikelet ripening (d) were recorded for every pot.

The total and effective tiller or panicle count in every pot was recorded before harvesting. Six representative panicles from each pail were selected and tagged then used to determine the number and percentage (%) of filled and unfilled spikelets per panicle, total spikelet number per panicle, and filled spikelet weight per panicle (g). Furthermore, all panicles in every pot were harvested, air-dried, and threshed. Filled spikelets were separated from unfilled spikelets and sun-dried until constant weight to determine their dry biomass or the grain yield (g). Rice straw was harvested by cutting it from the roots. Roots were carefully washed with water to remove attached soil particles. Straw and roots were sun-dried until constant weight to determine the dry straw and root weights (g). Harvest index was calculated using the following formula: Harvest index = Grain yield (g) / [Grain yield (g) + Straw weight (g)]. Soil depth (cm) data, indicating the ease and degree of soil proliferation of roots throughout crop growth, was also measured in every pot at the end of this greenhouse experiment.

Experimental Design, Data Analyses, Interpretation and Presentation

The study was set-up in a three - factor randomized complete block design. Each treatment combination was replicated 10 times.

The light intensity varied on different sections of the greenhouse; hence, the greenhouse was blocked by ensuring that every block would receive an equal amount of sunlight. All the blocks contained all eight treatment combinations.

The following skewed or non-normal figures were subjected into log transformation: root weight (g); harvest index; duration (d) from planting to panicle emergence and anthesis; tiller counts at 26, 54, 75, 82, and 89 DAP; LCC reading at 49 DAP; total leaf count at 14 DAP; green leaf counts at 28, 91, and 98 DAP; green leaf percentages at 21–35, 42, 49, and 63 DAP; dried leaf counts at 14, 28, and 70 DAP; dried leaf percentages at 14, 28, and 49 DAP; dotted leaf count at 14, 21, and 35 – 84 DAP; dotted leaf percentages at 14 – 84 DAP. The main and interaction effects of soil type, biomass application, and irrigation method on grain output and crop attributes were then evaluated by employing the multifactorial ANOVA in IBM® SPSS® Version 20 statistical package.

The observed significant three-way interaction on grain yield was explained by testing ANOVAs on grain yield and yield-contributing effects of biomass application (3rd factor) on soil type (1st factor) x irrigation method (2nd factor) interaction. Such ANOVAs were tested separately for experimental units applied and unapplied with biomass (How2statsbook 2019).

Biomass application influenced the interaction between soil type and irrigation method if the ANOVAs for experimental units applied with biomass had a different or opposite statistical significance with those of experimental units unapplied with biomass. The yield-contributing plant characteristics were used to explain the observed significant three-way interaction effect on grain yield.

Data on leaf greenness levels (LCC values), total tiller and total leaf counts; green, dotted, and dried leaf counts; and green, dotted, and dried leaf percentages were presented in 13 growth stages at 7-d interval to provide a comprehensive picture of the physiological processes occurring throughout the crop's life. Such data were used to explain the significant differences in grain yields obtained. Total tiller count indicates the crop's potential to produce panicles, which will serve as "sink" for photosynthates. Data on leaves show the degree and duration by which the leaves are performing photosynthesis and will be able to partition their photosynthates to the grains.

Environmental Factors

A handy thermometer-hygrometer instrument was used to manually read and record the daily 8:00 AM and 2:00 PM figures on relative humidity (%) and temperature (°C) (Table 2).

Table 2. Descriptive statistics for relative humidity and temperature at 1 – 98 d after planting.

Parameter	Mean	Median	Minimum	Maximum
Relative humidity, %				
8:00 AM	75.8	75.5	66.0	88.0
2:00 PM	72.4	70.0	60.0	87.0
Temperature, °C				
8:00 AM	29.1	29.0	21.0	36.0
2:00 PM	30.7	31.5	21.5	37.0

RESULTS AND DISCUSSION

Main Effects of Soil Type, Irrigation Method, and Biomass Application on Grain Yield and Yield Components

The main effects of soil type and irrigation method on grain yield and most of the yield component parameters were significant (Table 3), while the main effects of biomass application were insignificant.

Comparison of Yield Determinants between Sandy Loam Soil (SLS) and Loam Soil (LS)

Contrary to LS, the following significant results were observed in SLS: [a] grain yield, at 28.2 g pot^{-1}, was higher by 14%; [b] total and effective tiller counts, at 21.0 and 20.0 tillers per pot, were greater by 22 – 23%; [c] filled spikelet percentage, at 69.8%, was lower by 3%; [d] unfilled spikelet number and percentage, at 41.2 spikelets per panicle and 30.2%, were higher by 3 – 12% (Table 4). An earlier study also noted that, compared with clay loam soils, SLS had either statistically or numerically superior grain yields and effective tiller counts (Chae and Kim 2001).

Compared with LS, the following significant findings were noted in SLS: [a] straw weight at 37.4 g pot^{-1}, was higher by 29%; [b] root weight, at 17.8 g pot^{-1}, was greater by 72%; and [c] harvest index at 0.43, was lower by 6% (Table 5).

Duration from planting to panicle emergence (73.6 d), anthesis (75.7 d), and spikelet ripening (97.7 and 98.8 d) in SLS were significantly longer by 1.8 – 2.5 d, or 2 – 3% (Table 6).

Relative to LS, the tallest leaf in SLS had significantly greater LCC values by 3 – 16% at 21 – 49, 63, and 84 DAP (Fig. 2).

Compared with LS, the following significant findings were noted in SLS: [a] tiller count was 10–14% smaller during active tillering (19 – 26 DAP) but 7 – 26% higher from mid-tillering until harvesting (40 – 96 DAP) (Fig. 2); [b] total leaf count was 7% lower during active tillering (21–28 DAP) but 10 – 21% higher from mid-tillering until harvesting (35 –98 DAP) (Fig. 2).

Table 3. The *p*-values for main and interacting influences of soil type, irrigation method, and biomass application on grain yield and yield components.

Factor	Grain Yield, g pot^{-1}	Yield Components					
		Tiller Count per Pot	Effective Tiller Count per Pot	Filled Spikelets per Panicle		Unfilled Spikelets per Panicle	
				Number	%	Number	%
soil type	<0.001††	<0.001††	<0.001††	0.426	0.009††	<0.001††	0.009††
irrigation method	<0.001††	<0.001††	<0.001††	0.016†	0.014††	0.081	0.014††
biomass application	0.719	0.383	0.420	0.953	0.350	0.062	0.350
soil type x irrigation method	0.108	0.008††	0.041†	0.122	0.467	0.886	0.467
soil type x biomass application	0.367	0.003††	0.004††	0.223	0.111	0.114	0.111
irrigation method x biomass application	0.594	0.263	0.300	0.097	0.199	0.783	0.199
soil type x irrigation method x biomass application	0.044†	0.901	0.489	0.764	0.885	0.974	0.885

Different at $p < 0.05$ (†) and $p < 0.01$ (††) based on the multifactorial ANOVA; factors were soil type, irrigation method, and biomass application.

Table 4. Mean grain yield and yield components of the 2 soil types across irrigation methods and biomass applications.

Soil type	Grain Yield, g pot^{-1}	Yield components							
		Tiller Count per Pot	Effective Tiller Count per Pot	Total Spikelet Number per Panicle	Filled Spikelets per Panicle		Unfilled Spikelets per Panicle		Filled Spikelet Weight per Panicle (g)
					Number	%	Number	%	
sandy loam	28.21a	20.95a	19.98a	136.91a	95.68a	69.77b	41.23a	30.23a	1.90a
loam	24.75b	17.05b	16.38b	134.79a	98.03a	72.79a	36.76b	27.21b	1.95a

Unlike letters indicate the difference between soil types at $p < 0.05$.

Relative to LS, SLS had inferior leaf health status during active tillering (21 – 28 DAP), but better leaf health status at 35, 49, 63, and 70 DAP. These were noted to be significantly different in SLS: [a] green leaf count was 11 – 13% lower at 21 and 28 DAP, and 14 – 29% higher from mid-tillering to harvesting (35 – 98 DAP) (Fig. 3); [b] green leaf percentage was 4 – 6% smaller at 21 and 28 DAP, and 2 – 4% greater at 35, 63, and 70 DAP (Fig. 3); [c] dotted leaf count and percentage were 153 and 4% higher at 21 and 28 DAP, and 37 and 5% lower at 35 DAP (Fig. 4); [d] dried leaf number was 9 – 47% greater at 28, 42 and 56 – 98 DAP (Fig. 5); [e] dried leaf percentage was 2% greater at 28 DAP, and 1 – 2% smaller at 49 and 63 DAP (Fig. 5).

Mechanisms for Difference in Grain Yield between Sandy Loam Soil (SLS) and Loam Soil (LS)

Compared with LS, the significantly superior grain yield in SLS could be caused by its higher permeability to roots and water, and better balance among cationic soil nutrients. These soil conditions resulted in a healthier root system (Table 5), a higher capacity to either uptake or exclude soil nutrients, closer-to-the-optimum soil nutrient uptakes, and better yield-contributing crop traits (Figs. 2 – 5, Tables 4 – 6). The optimum level of soil nutrient uptake is above the deficient level but below the toxic level of nutrient uptakes, which results in healthy crops and superior yields.

Table 5. Mean plant organ weights, harvest index, and depth of the 2 soil types across irrigation methods and biomass applications.

Soil Type	Straw Weight, g pot^{-1}	Root Weight, g pot^{-1}	Harvest Index	Soil Depth at Harvest, cm
sandy loam	37.38a	17.83a	0.43b	16.55a
loam	28.96b	10.39b	0.46a	15.99b

Unlike letters indicate the difference between soil types at $p < 0.05$.

Table 6. Duration from planting to reproductive and spikelet ripening stages of the two soil types across irrigation methods and biomass applications.

Soil Type	Average Duration (d) from Planting			
	until panicle emergence	until anthesis	until three panicles in a pot become at least 80% brown	until 50% of the panicles in a pot become at least 80% brown
sandy loam	73.63a	75.70a	97.68a	98.83a
loam	71.18b	73.20b	95.38b	97.00b

Unlike letters indicate the difference between soil types at $p < 0.05$.

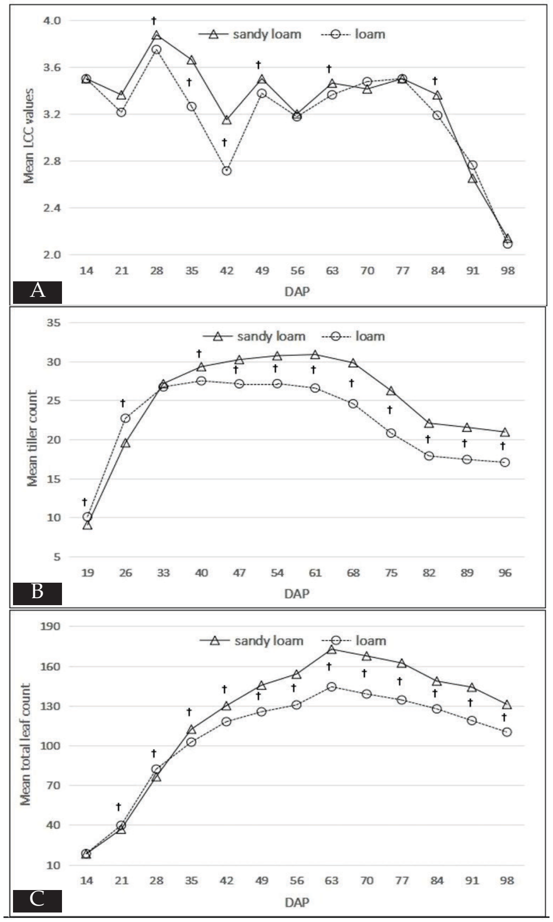

Fig. 2. Leaf color chart (LCC) values of the tallest leaf (A), tiller and total leaf counts (B, C) at various days after planting (DAP) of the 2 soil types across biomass applications and irrigation methods. Dagger (†) above or between the sandy loam vs. loam data indicate their difference at $p < 0.05$.

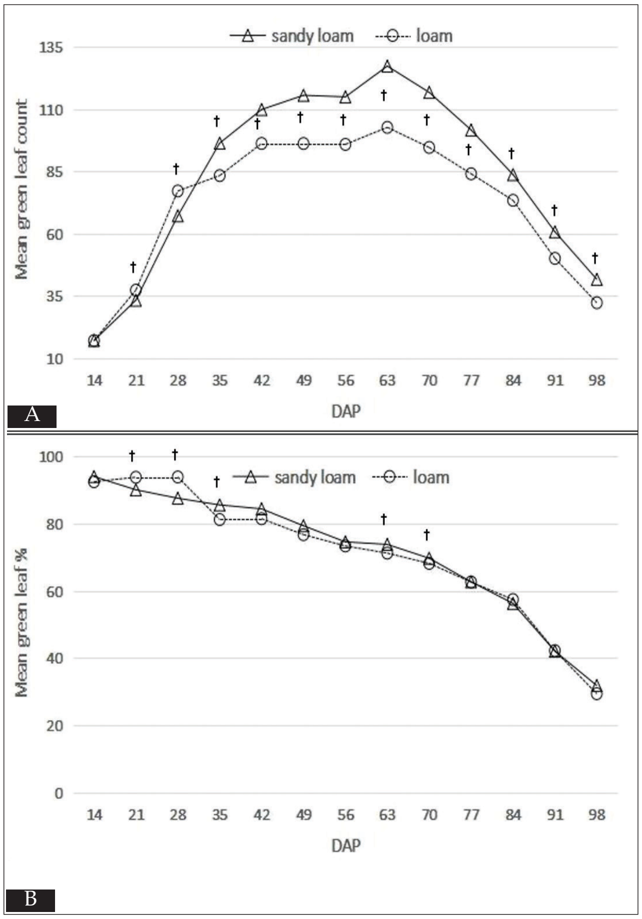

Fig. 3. Green leaf count (A) and percentage (%) (B) at various days after planting (DAP) of the 2 soil types across biomass applications and irrigation methods. Dagger (†) above or between the sandy loam vs. loam data indicate their difference at $p < 0.05$.

Contrary to LS, SLS had higher root and water permeability owing to its 4% greater sand fraction (Table 1). Furthermore, the significantly greater soil depth and root weight (Table 5) in SLS indicates that it was less compact, allowing a better degree of root and water penetration through its pore spaces.

Relative to LS, SLS also had a 2% greater clay level (Table 1); hence, SLS held more water than LS (Table 1). In this study, water was regularly added to maintain the same water levels in pots assigned as SLS or LS treatment. Excess water, which was not adsorbed by the soil or taken up by the roots, was retained in the pots since the pots used did not have holes at the bottom. Compared with LS, water held in SLS was more accessible for root absorption.

As more roots penetrate and grow through SLS, more soil particles are pushed upward, resulting in a less compact and thicker soil (Table 5) with a higher total porosity for holding greater amounts of water and other soil nutrients. This allowed the roots to come into contact with more soil nutrients, resulting in better or closer-to-the-optimum level of soil nutrient uptakes.

An earlier study reported that sandy soils had a higher pore frequency and larger macropore size, contributing to better soil penetration of roots (Kar et al. 1979). The same study also found superior root growth in SLS than in LS. A past experiment noted that, in the -10, -100, and -1 000 kPa soil water potentials, the root elongation rate was significantly highest in loose soil, followed by lightly compact soil, and lastly by heavily compact soil (Iijima et al. 2007). An earlier study's report on root weights in various soil depths had seen longer roots or deeper root penetrations in SLS than in clay loam soil (Chae and Kim 2001). The same study also found greater total root weights, water percolations, rice yield components, and grain output in SLS than in clay loam soil; greater percolation was primarily due to the profuse growth of roots.

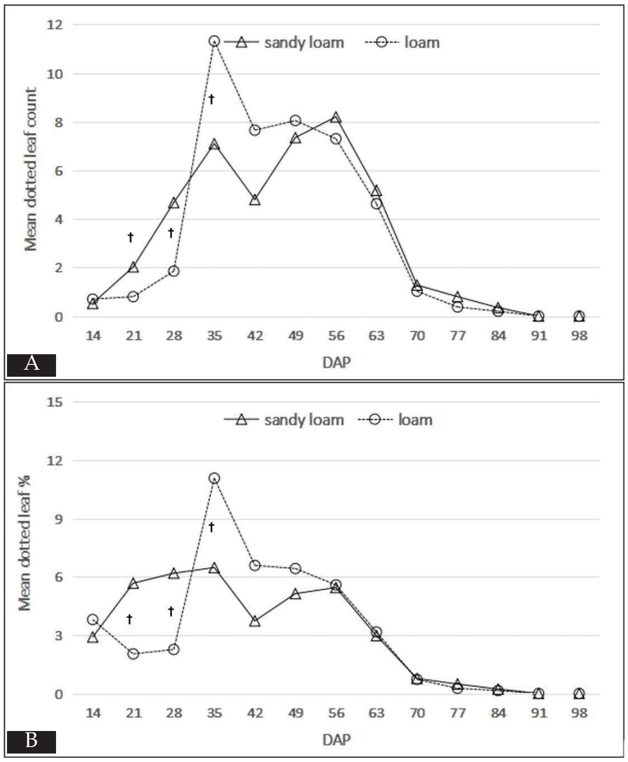

Fig. 4. Dotted leaf count (A) and percentage (%) (B) at various days after planting (DAP) of the 2 soil types across biomass applications and irrigation methods. Dagger (†) above or between the sandy loam vs. loam data indicate their difference at *p* < 0.05.

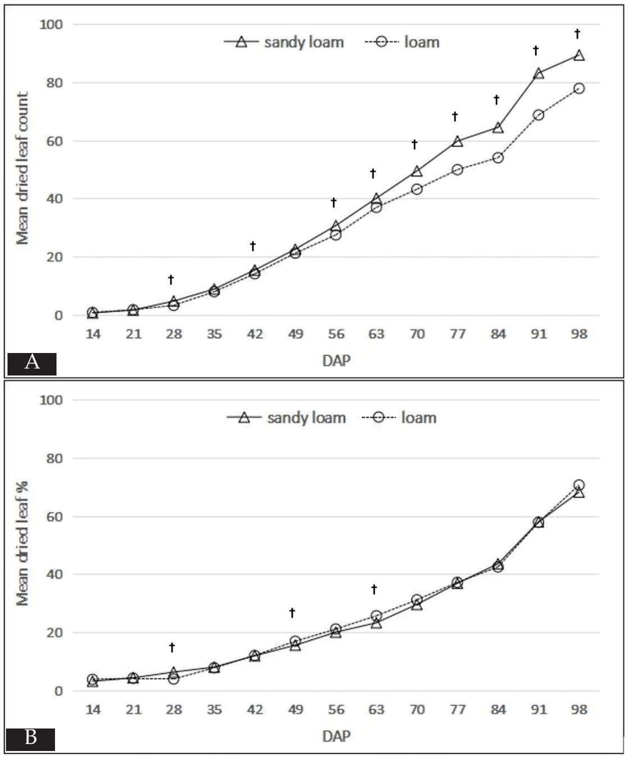

Fig. 5. Dried leaf count (A) and percentage (%) (B) at various days after planting (DAP) of the 2 soil types across biomass applications and irrigation methods. Dagger (†) above or between the sandy loam vs. loam data indicate their difference at *p* < 0.05.

Relative to LS, the SLS had lower amounts of soil exchangeable cationic nutrients, resulting in reduced restriction of potassium (K) uptake and closer-to-the-optimum K uptake. SLS had a lower exchangeable K level by only 0.007 $cmol_c$ kg^{-1} or 2%. However, its exchangeable cations were less restrictive to K uptake since it had lower levels of calcium (Ca) by 0.06 $cmol_c$ kg^{-1} or 2% and magnesium (Mg) by 1.99 $cmol_c$ kg^{-1} or 7%, resulting in a lower (Ca+Mg): K ratio (Table 1). This reduced restriction to K uptake was reflected in the milder K deficiency of SLS in the nutrient omission experiment. The minus K treatment of the nutrient omission setup, showed the following: [a] tiller count was greater in SLS, and [b] percentage of tillers, and straw and root weight were higher in SLS relative to those of rice plants supplied with a complete set of nutrients (Fig. 1). The closer-to-the-optimum K uptake was also seen in the significantly lower (*p*-value=0.001**) root: shoot weight ratio in SLS (1:4.2) than LS (1:5.5), indicating a better K status in SLS. Leaves of K-deficient crops usually store carbohydrates; they have less ability to translocate photosynthates to their roots and seldom increase root weight (Hermans et al. 2006). It was also reported earlier that sufficient or higher K levels led to greater root growth (Jia et al. 2008) and root-to-straw weight (Cai et al. 2012).

Compared with LS, the closer-to-the-optimum soil K uptake in SLS had a greater contribution to closer-to-the-optimum soil nitrogen (N) uptake. The milder K and N deficiencies of SLS were seen in the nutrient omission results (Fig. 1). In the minus N treatment of the nutrient omission setup, the following were noted: [a] tiller count, straw and root weight, and crop height were greater in SLS, and [b] percentage of all the data in number 1 relative to those of rice plants supplied with a complete set of nutrients were higher in SLS (Fig. 1). Moreover, the closer-to-the-optimum N uptake was observed in [a] the leaf greenness levels or LCC values (Fig. 2), which were significantly higher at 21 – 49, 63, and 84 DAP despite the nutrient dilution from the greater tiller and total leaf counts from mid-tillering until harvesting (Fig. 2), and [b] the significantly longer duration from planting until panicle emergence, anthesis, and maturity (Table 6). Similar results were seen in past field experiments. Applying the same N amount of 120 kg ha^{-1}, the [a] available soil K and N levels, [b] K and N uptakes, [c] yield components, and [d] grain yields were highest in plots added with 70 kg K ha^{-1}, followed by 60 kg K ha^{-1}, and lastly by 50kg K ha^{-1} (Murthy et al. 2015). Under the same N level at 0, 180, and 270 kg ha^{-1}, the [a] N and K uptakes, [b] N use efficiencies, [c] yield components, and [d] grain yields were significantly greatest in plots applied with 180 K ha^{-1}, followed by 160 K ha^{-1}, and lastly by 0 K ha^{-1} (Ye et al. 2021).

The closer-to-the-optimum level of soil nutrient uptake during the plants' vegetative stage and the significantly longer duration from planting until panicle emergence and anthesis (Table 6) allowed them to produce more chlorophyll (CHL) for a longer time. Hence, in this study, the following significant findings were noted in SLS: [a] LCC values, which indicates leaf CHL levels, were higher at 21 – 49 and 63 DAP (Fig. 2); and [b] better leaf health status at 35, 49, and 63 DAP (Fig. 3 – 5).

Closer-to-the-optimum level of soil nutrient uptake, a longer vegetative stage, greater leaf CHL status, and superior leaf health condition enabled the rice crop to collect more reactants for photosynthesis (PS) and photosynthesize for a longer duration. This possibly led to higher net and total PS, allowing the plants to produce more photosynthates. These conditions resulted in synthesizing and maintaining more root, shoot, and panicle tissues. As such, the significantly greater [a] tiller and total leaf counts from mid-tillering until anthesis (Fig. 2), [b] effective tiller or panicle count (Table 4), and [c] straw and root weights (Table 5) were noted. Greater root weight enhanced the plants' ability to either uptake or exclude soil nutrients, which supported PS and the synthesis of new tissues.

The enhanced shoot and root organs were an improvement in "source"; a higher number of panicles was an enhancement in "sink". Better "source" (LCC values, leaf health status, tiller and total leaf counts, and straw and root weights) during spikelet filling (Figs. 2 – 5 and Table 5), along with the improved "sink," allowed the transport of more photosynthetic products and nutrients into spikelets, leading to a superior grain yield under SLS.

Comparison of Yield Determinants Between CF and CI

The grain yield of CF, at 28.4 g pot^{-1}, was statistically greater by 15% than CI (Tables 3 and 7). Compared with CI, significant results on yield components of CF were also noted: [a] total and effective tiller counts, at 20.1 and 19.0 tillers per pot, were greater by 9 – 12%; [b] filled spikelet number and percentage, at 100.5 spikelets per panicle and 72.7%, were higher by 3 – 8%; [c] unfilled spikelet percentage, at 27.3%, was lower by 3%. Earlier greenhouse experiments of soil collected from the same rice area and exposed to identical irrigation methods also found that CF had a statistically superior grain output of 7% (Magahud and Padios 2022). In prior studies, CF also had significantly or numerically higher grain yields than the following CI variations: [a] watering when soil water tension dropped to -30 kPa (Chu et al. 2018a; Chu et al. 2018b), and [b] irrigating if water depths reached 12 – 15 cm beneath the soil surface (Islam et al. 2018; Jiang et al. 2023). Effective tiller or panicle counts (Chu et al. 2018a; Chu et al. 2018b), and filled spikelet number (Jiang et al. 2023) and percentage (Chu et al. 2018a; Chu et al. 2018b) were also noted to be significantly or numerically higher in CF.

Straw weight in CF, at 34.8 g pot^{-1}, was statistically greater by 11% (Table 8). Earlier greenhouse experiments of the same soil and irrigation treatments also showed that CF had significantly higher straw weight by 9% (Magahud and Padios 2022). Significantly or numerically greater straw weights in CF were also reported by Islam et al. (2018), Chu et al. (2018a; 2018b), and Jiang et al. (2023).

Root weight in CF, at 15.5g pot^{-1}, was statistically greater by 22% (Table 8). Similarly, root weights and root oxidation activity were noted by Chu et al. (2018a; 2018b) to be significantly or numerically higher in CF.

In CF, leaf greenness levels or LCC values of the top-most expanded leaf were significantly greater by 4% at 42 DAP (Fig. 6). Past greenhouse studies also revealed that CF had significantly higher [a] LCC values at 35 and 91 DAP; [b] SPAD values (or CHL levels) at 29 – 43 DAP (Magahud and Padios 2022); and [c] SPAD values in three fertilizer treatments for 1 – 3 crop stages (Magahud et al. 2019).

Compared with CI, CF had either the same or significantly lower total tiller count from early tillering until early panicle initiation, or 19 – 54 DAP; total tiller count was statistically smaller by 5 – 8% at 19 and 33 DAP (Fig. 6). CF, however, had significantly higher total tiller count from panicle initiation until harvesting (61 – 100 DAP) (Fig. 6, Table 7). Likewise, earlier greenhouse experiments showed that the total tiller count in CF was significantly lower at 19 – 54 DAP (Magahud and Padios 2022) and at 47 – 58 DAP in two fertilizer treatments (Magahud et al. 2019), but numerically higher during harvest (Magahud and Padios 2022).

It was noted that the thin tillers had been withering from the plants at 68 – 96 DAP for CF and 61 – 96 DAP for CI; hence, during these crop stages, decreasing trends in the total tiller counts under both irrigation methods were seen. The thin tillers of CF and CI were unable to bear panicles and died before harvesting.

Compared with CI, the number of thin tillers in CF was greater at 19 – 40 DAP but the same at 47 – 96 DAP, while the number of robust tillers was lower at 19 – 40 DAP but higher at 47 – 96 DAP. These were because the thin tillers in CF were becoming healthier at 47 – 54 DAP, thus the observed greater effective tiller count at harvest (Table 7). The robust tillers of CF and CI had yielded panicles and lasted up to harvesting.

In CF, total leaf count was significantly lower by 3 – 5% during active tillering (21 and 28 DAP), but significantly greater by 2 – 6% from

Table 7. Mean grain yield and yield components of the 2 irrigation methods across soil types and biomass applications.

Irrigation Method	Grain yield g pot^{-1}	Yield Components							
		Tiller Count per Pot	Effective Tiller Count per Pot	Total Spikelet Number per Panicle	Filled Spikelet per Panicle		Unfilled Spikelets per Panicle		Filled Spikelet Weight per Panicle (g)
					Number	%	Number	%	
continuously flooded	28.39a	20.10a	19.00a	138.23a	100.45a	72.68a	37.78a	27.32b	2.00a
controlled irrigation	24.57b	17.90b	17.35b	133.50a	93.26b	69.87b	40.24a	30.13a	1.85a

Unlike letters indicate the difference between irrigation methods at $p < 0.05$.

Table 8. Mean plant organ weights, harvest index, and soil depth of the 2 irrigation methods across soil types and biomass applications.

Irrigation Method	Straw Weight, g pot^{-1}	Root Weight, g pot^{-1}	Harvest Index	Soil Depth at Harvest, cm
continuously flooded	34.83a	15.48a	0.45a	18.46a
controlled irrigation	31.50b	12.73b	0.44a	14.08b

Unlike letters indicate the difference between irrigation methods at $p < 0.05$.

late tillering until spikelet ripening (49 – 91 DAP) (Fig. 6). In an earlier experiment, leaf area indices from heading to maturity were also significantly or numerically higher in CF (Chu et al. 2018a; Chu et al. 2018b).

Relative to CI, CF had better leaf health at an early stage (14 DAP) and from panicle emergence until harvesting (70 – 98 DAP), but poorer leaf health during tillering (28 – 56 DAP). These were seen to be significantly different in CF: [a] green leaf count was 5 – 16% greater at 63 – 98 DAP and 4 – 6% smaller at 21 and 28 DAP (Fig. 7); [b] green leaf percentage was 2 – 4% higher at 14 and 70 – 98 DAP, and 5% lower at 35 DAP (Fig. 7); [c] dotted leaf count and percentage were 46 and 2% higher at 21 DAP; [d] dried leaf count was 20 – 68% smaller at 14 and 21 DAP and 7 – 18% greater at 42 – 63 DAP (Fig. 8); and [e] dried leaf percentage was 1 – 3% lower at 14, 21 and 70 – 98 DAP and 1 – 2% higher at 42 and 49 DAP (Fig. 8). Prior greenhouse experiments also revealed that, contrary to CI, CF had [a] superior leaf health from spikelet filling to harvesting, yet inferior at tillering (Magahud and Padios 2022); [b] and significantly or numerically higher healthy above-ground biomass and lower unhealthy leaf weights of rice exposed to six fertilizer treatments and harvested at 59 DAP (Magahud et al. 2019).

Mechanisms for Difference in Grain Yield between CF and CI

PSB Rc 18, the rice variety used in this study, was developed for an irrigated lowland ecosystem (PhilRice 2011). The genetic composition of this variety is more efficient in converting the growth factors (sunlight, carbon dioxide, water, and other soil nutrients) into photosynthates in CF than in CI condition. Hence, its better performance under CF is expected.

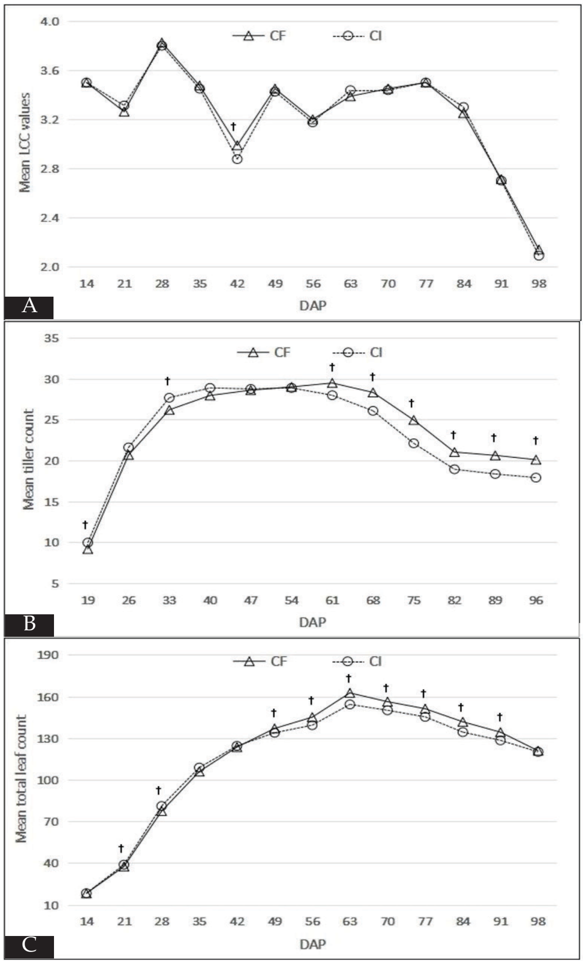

Fig. 6. Leaf color chart (LCC) values of the tallest leaf (A), and tiller and total leaf counts (B, C) at various days after planting (DAP) of the 2 irrigation methods across soil types and biomass applications. Dagger (†) above the continuously flooded (CF) vs. controlled irrigation (CI) data indicate their difference at $p < 0.05$.

The statistically greater grain yield in CF (Tables 3 and 7) was because it induced the plant to produce and maintain more robust tillers from 47 until 51 DAP and retain these robust tillers until harvesting (Table 6B), which led to better yield-contributing crop traits. In contrast to thin tillers, the robust tillers had [a] more or healthier roots (Table 8), which can absorb and conduct higher amounts of water and other soil nutrients to support PS and synthesis of new root, shoot, panicle, and grain tissues; and [b] leaves with greater total surface area, which can produce more photosynthates for maintaining the tillers' health, producing panicles, and filling in spikelets. These explain [a] the greater root and straw weight (Table 8); [b] LCC values (indicative of CHL levels), which were either the same or higher across the crop's life (Fig. 6), despite supporting the significantly higher tiller count at 61 – 96 DAP and greater total leaf count at 49 – 91 DAP (Fig. 6); [c] the statistically greater effective tiller or panicle count (Table 7); and [d] the higher leaf health condition at spikelet filling (Figs. 7 – 8). A better "source," along with the improved "sink," allowed the translocation of more photosynthetic products and nutrients into more spikelets, leading to a superior grain yield in CF than CI (Tables 3 and 7).

The higher grain yield in CF over CI (Tables 3 and 7) can be explained by greater available soil N, resulting in superior yield-determining crop characteristics. Magahud et al. (2019) previously showed greater available N status in CF soil collected from the same area being studied. A far greater ammonium N level was also observed under CF (Madhavi et al. 2022). Smaller N releases into the air (Verhoeven et al. 2018; Shekhar et al. 2021) can be the reason for the higher available soil N.

Owing to the higher soil N availability, the roots absorbed a higher amount of N and translocated to the different parts of the crop during the vegetative stage. This could have resulted in additional N for synthesizing more root, shoot, panicle, and grain tissues; hence the significantly greater growth and yield parameters in CF.

In the two soil types being studied, N had the highest insufficiency level of all the soil-derived vital elements. Compared with the other nutrient omission treatments established, the plants under the minus N treatment showed the lowest tiller counts and shortest crop height in SLS and LS, and least shoot weight in LS (Fig. 1). Hence, in this study, the slightly higher available N in CF compared with the CI soil can explain the significantly superior yield in CF.

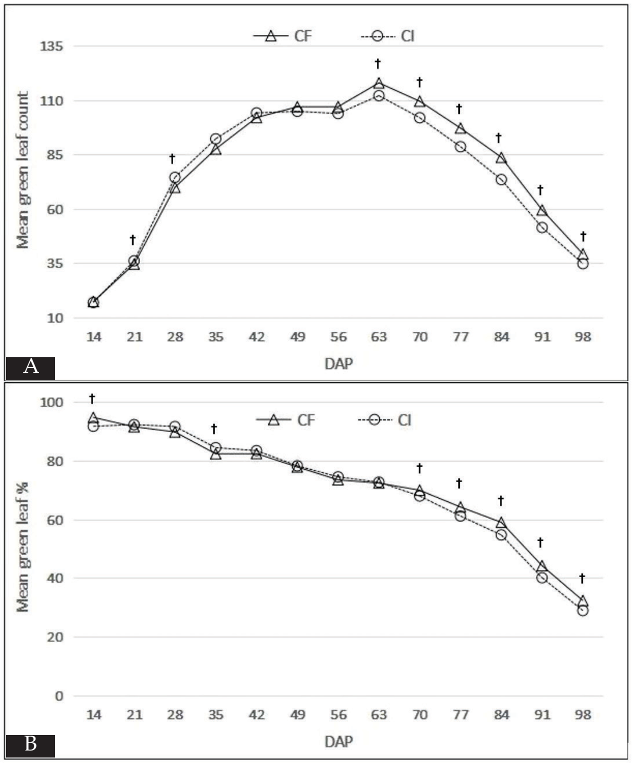

Fig. 7. Green leaf count (A) and percentage (%) (B) at various days after planting (DAP) of the 2 irrigation methods across soil types and biomass applications. Dagger (†) above the continuously flooded (CF) vs. controlled irrigation (CI) data indicate their difference at $p < 0.05$.

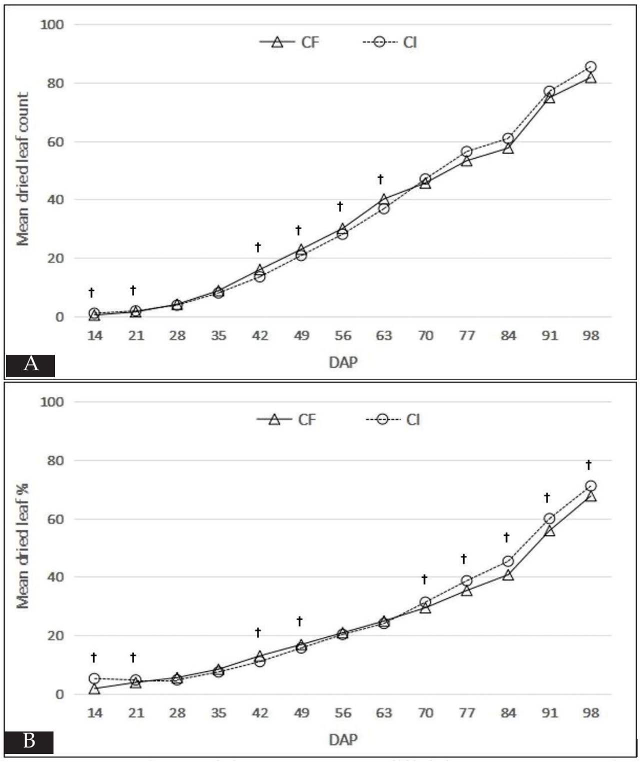

Fig. 8. Dried leaf count (A) and percentage (%) (B) at various days after planting (DAP) of the two irrigation methods across soil types and biomass applications. Dagger (†) above the continuously flooded (CF) vs. controlled irrigation (CI) data indicate their difference at $p < 0.05$.

Interacting Influence of Soil Type, Irrigation Method, and Biomass Application on Grain Yield and Yield Components

The three experimental factors had an insignificant two-way interacting influence on grain yield (Table 3). However, the interacting influences of soil type x irrigation method and soil type x biomass application on total and effective tiller counts were significant. Moreover, a significant three-way interacting influence on grain yield was also noted.

Comparisons in Grain Yield and Yield-determining Effects of Biomass Application (Applied vs. Unapplied with Biomass) on Soil Type x Irrigation Method Interaction

Biomass application modified the soil type x irrigation method interaction due to the following statistical results: (1) the degree to which CF was exhibiting higher grain yield than CI was significantly greater (*p*-value = < 0.001**) in SLS than in LS for experimental units or pots applied with biomass (Fig. 9A); and (2) the level at which CF was attaining greater grain yield than CI was statistically similar (*p*-value = 0.754) in SLS and LS for pots unapplied with biomass (Fig. 9B).

In pots applied with biomass, significant interactions were noted in the following crop traits: [a] filled spikelet number per panicle, [b] root biomass, [c] green leaf percentage, and [d] dried leaf count and percentage (Table 9). Each of these interactions had either an enhancing or degrading effect on the crop. These significant interactions, however, were not observed on the same crop traits in pots unapplied with biomass; hence, the same level of either an enhancing or deteriorating effect would be observed in SLS and LS if the irrigation method was changed from CI to CF and vice versa.

In pots applied and unapplied with biomass, significant interactions were observed in tiller, total leaf, and green leaf counts (Table 9). Each of these interactions had either a positive or negative effect on the crop.

Mechanisms for the Difference in Grain Yield Effects of Biomass Application (Applied vs. Unapplied with Biomass) on Soil Type x Irrigation Method Interaction

In pots applied with biomass, the degree at which CF was exhibiting higher grain yield than CI was significantly greater in SLS than LS (Fig. 9A) because, compared with CI, CF had a statistically higher filled spikelet number, root weight, and green leaf percentage in SLS than LS (Table 9). A higher filled spikelet number was an improvement in "sink", which meant more vessels to contain the photosynthates. Greater root weight allowed the plants to consume more water plus essential soil elements for performing PS, synthesizing and maintaining plant tissues and organs, and spikelet filling. Higher green leaf percentage allowed the plants to achieve greater net PS for synthesizing and maintaining plant tissues and organs, and spikelet filling.

In pots unapplied with biomass, the interactions between soil type and irrigation method were insignificant in most yield-contributing crop traits (Table 9); hence, the insignificant interaction in grain yield was observed (Fig. 9B). The level at which CF was attaining greater grain yield than CI was statistically the same in SLS and LS (Fig. 9B) because, compared with CI, CF had statistically similar filled spikelet number, root weight, green leaf percentage, and dried leaf number and percentage in the two soil types (Table 9). Furthermore, insignificant interactions were observed in most of the yield-contributing crop traits mentioned in this study's materials and methods section; thus, the same level of either enhancing or degrading effects would be observed in SLS and LS if the irrigation method was changed from CI to CF and vice versa.

Water levels, "source" and "sink" characteristics, other yield-contributing characteristics, and grain yields of SLS were either closer to the optimum or significantly higher than LS (Tables 3 – 6, Figs. 2 – 5), and those of CF were either closer to the optimum or significantly greater than CI (Tables 3, 7 and 8; Figs. 6 – 8). Hence, it can be inferred that rice under SLS and CF had a higher potential grain yield and optimum nutrient requirement.

Applying rice biomass supplied additional macro and micronutrients, which caused the rice under SLS and CF treatments to raise their soil nutrient supply closer to the optimum nutrient requirement, manufacture more photosynthates for synthesizing new plant tissues and organs and filling in spikelets, and produce higher grain yields in such treatments. These conditions resulted in a wider gap among the grain yields of soil type x irrigation method interactions; thus, the unparalleled or converging lines in Fig. 9A. Likewise, it was reported earlier by Witt and Dobermann (2002), Xu et al. (2015), and Che et al. (2016) that N, P, and K uptakes in field experiments were enhanced with increasing grain yield levels. These studies also suggested that fertilizer NPK requirements or recommendations should be raised with increasing grain yield levels.

Not applying rice biomass maintained the soil nutrient supply at a level far below the optimum nutrient requirement of rice under SLS and CF; this caused the rice plants in such treatments to manufacture fewer photosynthates and produce lower grain yields. These factors caused a smaller gap among the grain yields of soil type x irrigation method interactions; thus, the parallel lines in Fig. 9B.

The soil type x irrigation method interactions of filled spikelet number per panicle, root weight, tiller count, total leaf count, green leaf count and percentage, and dried leaf count and percentage had a different or opposite statistical significance for applied vs. unapplied biomass (Table 9). These were also due to the higher optimum nutrient requirement and potential grain yield in pots applied than those unapplied with biomass.

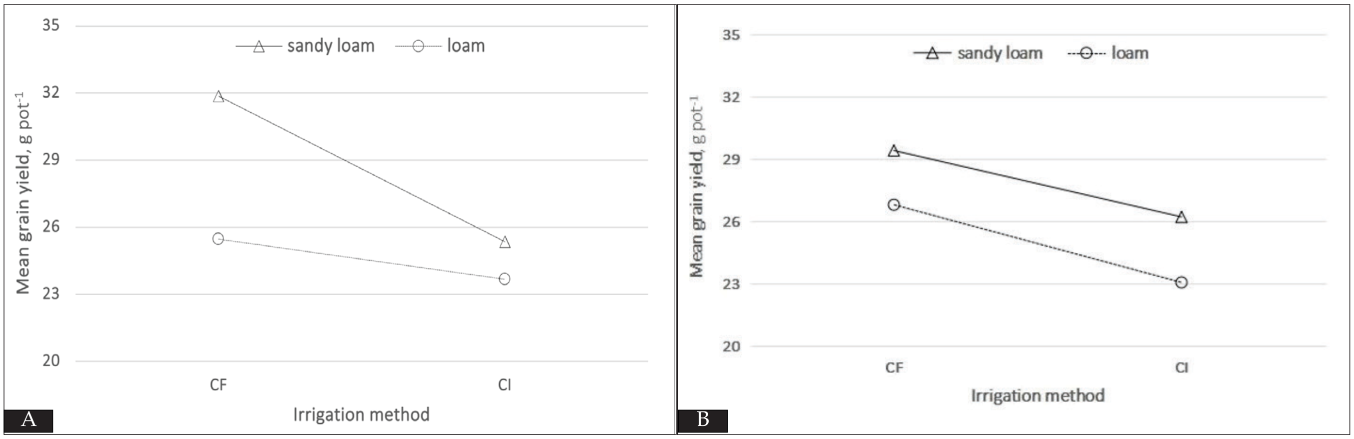

Fig. 9. Mean grain yield of experimental units applied with biomass (A) and those unapplied with biomass (B); grain yields presented as the interaction of 2 soil types and 2 irrigation methods; irrigation methods were continuously flooded (CF) and controlled irrigation (CI); interaction was significant using the ANOVA only in experimental units applied with biomass.

Table 9. Comparison in yield-contributing effects of biomass application on soil type x irrigation method interaction.

Yield-determining Crop Trait	Significant ($p < 0.05$) Soil Type x Irrigation Method Interaction	
	Applied with Biomass	**Unapplied with Biomass**
Filled spikelet number per panicle	The degree at which CF was exhibiting a greater filled spikelet number was greater in SLS than in LS	No significant interaction
Root weight	The level at which CF was showing greater root weight was higher in SLS over LS	No significant interaction
Tiller count	Relative to CI, the following results were observed in CF: fewer tillers in SLS, while more tillers in LS at 33 DAP.	Compared with CI, the following results were observed in CF: fewer tillers in SLS, while more tillers in LS at 26, 33, and 40 DAP.
	The level at which CF was showing fewer tillers than CI was higher in SLS over LS at 40 DAP.	The degree at which CF was exhibiting more tillers than CI was higher in SLS over LS at 82 and 89 DAP
	The degree at which CF was exhibiting more tillers than CI was higher in SLS over LS at 96 DAP	
Total leaf count	The level at which CF was showing a lower total leaf count than CI was greater in SLS than LS at 35 DAP.	Relative to CI, CF had a lower total leaf count in SLS, while higher total leaf count in LS at 28, 35, and 42 DAP.
	Compared with CI, CF had a lower total leaf count in SLS, while a higher total leaf count in LS at 35 and 42 DAP.	
Green leaf count	The level at which CF was showing a lower green leaf count than CI was higher in SLS over LS at 28 DAP.	Compared with CI, CF had lower green leaf count in SLS but higher green leaf count in LS at 28, 35, and 42 DAP.
	Compared with CI, the following findings were noted in CF: [a] green leaf count was lower in SLS, but higher in LS at 35 and 42 DAP, and [b] green leaf count was greater in SLS but either the same or lower in LS at 70 DAP.	Relative to CI, CF had a higher green leaf count in SLS but a lower green leaf count in LS at 98 DAP.
Green leaf percentage	Relative to CI, the following findings were noted in CF: [a] green leaf percentage was higher in SLS, but lower in LS at 28 DAP; [b] green leaf percentage was greater in SLS but almost the same in LS at 70 DAP.	No significant interaction
Dried leaf count	Compared with CI, the following results were observed in CF: [a] dried leaf count was either the same or higher in SLS, but lower in LS at 21 and 28 DAP; [b] dried leaf count was greater in SLS, but almost the same in SLS at 70 DAP.	No significant interaction
Dried leaf percentage	Relative to CI, the following findings were noted in CF: dried leaf percentage was higher in SLS, while lower in LS at 21, 28, and 42 DAP.	No significant interaction

Note: No significant interactions in all other yield-contributing crop parameters mentioned in the materials and methods section.

Recommendations on Soil Type, Irrigation Method, and Biomass Application for Enhancing Rice Production

In Agusan, growing rice in Butuan sandy loam soil should be preferred over Butuan loam soil. CF is recommended over CI in soils with mild or no zinc deficiency issues, like the ones being studied. CF can be employed in zinc-deficient fields, where farmers usually apply zinc. CI is recommended specifically in water-scarce locations since it produced a statistically smaller grain output in this study.

CONCLUSION

Relative to Butuan loam soil, Butuan sandy loam soil had a statistically greater grain output by 3.82 g pot^{-1} or 14% since it had higher root and water permeability and better balance among soil nutrients, leading to closer-to-the-optimum soil nutrient uptakes and superior yield-determining crop attributes. Such attributes were statistically higher leaf greenness levels by 0.10 – 0.44 leaf color chart (LCC) values or 3 – 16% at tillering, panicle initiation, and spikelet filling; better leaf health status at tillering and panicle initiation; higher tiller and total leaf counts from mid-tillering until harvesting; higher effective tiller count by 3.60 tillers pot^{-1} or 22%; greater root weight by 7.44 g pot^{-1} or 72%; and higher straw weight by 8.42 g pot^{-1} or 29%. Contrary to controlled irrigation (CI), the continuously flooded (CF) setup had a statistically superior grain output by 3.82 g pot^{-1} or 15% because it induced the plants to produce and maintain a higher number of robust tillers from early panicle initiation until harvesting. This higher number of robust tillers led to significantly greater root weight by 2.75 g pot^{-1} or 22%, higher straw weight by 3.33 g pot^{-1} or 11%, greater effective tiller count by 1.65 tillers pot^{-1} or 10%, higher total leaf count by 3.10 – 8.28 leaves or 2 – 6% from early panicle initiation until spikelet filling, and superior leaf health condition during spikelet filling. Furthermore, the soils exposed to CF had more available N in the soil, which led to superior yield - determining crop attributes. Biomass application also substantially affected the soil type x irrigation method interaction. In pots applied with biomass, the degree at which CF was exhibiting higher grain yield than CI was significantly greater in sandy loam soil (SLS) than loam soil (LS) because, compared with CI, CF had statistically higher filled spikelet number, root weight, and green leaf percentage in SLS than LS. In pots unapplied with biomass, the interactions between soil type and irrigation method were insignificant in most yield - contributing plant traits; hence, an insignificant interaction in grain yield was observed.

The findings of this greenhouse study imply that, in Agusan, rice crop traits and grain yields are higher if grown in Butuan sandy loam than in Butuan loam soil, and employed with CF than with CI. The expected grain yields and optimum nutrient requirements of rice grown in other major lowland soil series in Caraga can also be studied to generate information on how these soils can be properly and specifically managed. Moreover, in addition to root biomass, root length data should be gathered in growth and productivity experiments in different soil types and irrigation methods. The significant results of this greenhouse study must be validated in the field, where the ratio, proportions, or balance of available soil nutrients and water at any given growth stage could be different. Furthermore, the grain yield-enhancing effects of different kinds of organic materials on Butuan soil could be investigated.

ACKNOWLEDGMENT

Sheena Lourdes P. Dalumpines; Agapito E. Lincuna, Jr. -- conceived, designed, and conducted the research.

Warrien A. Vitor, Julius Paul B. Guquib-- conducted the research.

Cris Mae T. Necesito-- English-edited the manuscript.

REFERENCES CITED

AGTING CS, ESTACION CS, ESTOY GF JR., COLLADO WB, REGALADO MJC, BURESH RJ. 2017. Performance of Rice Crop Manager in Agusan del Norte. Philipp J Crop Sci. 42(supplement 1):145. https://agris.fao.org/search/en/providers/122430/records/64745c0d542a3f9f03b50368.

AMAS JC, SOLENAD MF, TABUDLONG RL, JABAGAT GD, MAMALIS RP, ERANA MA, WAGAS AF. 2017. Participatory varietal selection of next-generation rice varieties in major ecosystems in the Caraga region. Philipp J Crop Sci. 42(supplement 1):113. https://agris.fao.org/search/en/providers/122430/records/6473b0c013d110e4e7a98ff2.

BARCENA NGP. 2022. DA introduces Abonong Swak to farmers in Cortes, SurSur. Philippine Information Agency. https://mirror.pia.gov.ph/press-releases/2022/10/28/da-introduces-abonong-swak-to-farmers-in-cortes-sursur.

BURDEOS CA, BATAY-AN EH. 2012. Field assessment of bacterial leaf blight, *Xanthomonas oryzae* pv. oryzae in RTR, Agusan del Norte. Proceedings of the 43rd PMCP Anniversary and Annual Scientific Conference; 2012 May 8 – 11; Cagayan de Oro City, Philippines. p. 94.

BURESH RJ, REGALADO MJC, COLLADO WB. 2015. Field evaluation of Rice Crop Manager: a comprehensive decision support tool for increasing yield and income for farmers in the Philippines. 2014 National Rice R & D Highlights. Agusan del Norte, Philippines: PhilRice Agusan.

CAI J, CHEN L, QU H, LIAN J, LIU W, HU Y, XU G. 2012. Alteration of nutrient allocation and transporter genes expression in rice under N, P, K, and Mg deficiencies. Acta Physiol Plant. 34:939–946. doi:10.1007/s11738-011-0890-x.

CARATING RB, GALANTA RG, BACATIO CD. 2014. The soils of the lowlands. In: The soils of the Philippines. Springer Netherlands. p. 51–106. doi:10.1007/978-94-017-8682-9.

CHAE JC, KIM SW. 2001. Effect of soil texture on rice growth and paddy soil percolation under lysimeter condition. Kor J Crop Sci. 46(3):236–240. https://koreascience.kr/article/JAKO200111922228401.pdf.

CHE SG, ZHAO BQ, LI YT, YUAN L, LIN ZA, HU SW, SHEN B. 2016. Nutrient uptake requirements with increasing grain yield for rice in China. J Integr Agr. 15(4):907–917. doi:10.1016/S2095-3119(15)61143-1.

CHU G, CHEN T, CHEN S, XU C, WANG D, ZHANG X. 2018. Agronomic performance of drought-resistance rice cultivars grown under alternate wetting and drying irrigation management in southeast China. Crop J. 6(5):482–494. doi:10.1016/j.cj.2018.04.005.

CHU G, CHEN T, CHEN S, XU C, WANG D, ZHANG X. 2018. The effect of alternate wetting and severe drying irrigation on grain yield and water use efficiency of *Indica - japonica* hybrid rice (*Oryza sativa* L.). Food Energ Secur. 7(2):e00133. doi:10.1002/fes3.133.

[DA Caraga] Department of Agriculture Caraga. 2022. DA Caraga taps media practitioners to promote Abonong Swak. Philippine Information Agency. https://mirror.pia.gov.ph/press-releases/2022/08/05/da-caraga-taps-media-practitioners-to-promote-abonong-swak.

[DA IV-CALABARZON] Department of Agriculture Region IV - CALABARZON. 2022. Tipid ka sa abonong swak! Philippines: DA-Bureau of Soils and Water Management, DA-Agricultural Training Institute, DA-Philippine Rice Research Institute. 2 p.

[DA-PHILRICE] Department of Agriculture-Philippine Rice Research Institute. 2022. PalayCheck system for the Philippine irrigated lowland rice. Pinoy Rice Knowledge Bank. https://www.pinoyrice.com/palaycheck/.

DESCALSOTA JP, MAMARIL CP, CORTON TM, DE DIOS JL, YABES SI. 2002. Minus-one element technique: nutrient deficiency test made easy, 2nd edition. Nueva Ecija, Philippines: Philippine Rice Research Institute. 12 p.

DOBERMANN A, FAIRHURST TH. 2000. Rice nutrient disorders and nutrient management, 1st edition. Singapore: Potash and Phosphate Institute. 191 p.

GOMEZ EJ. 2022. 'Abonong Swak' campaign launched. The Manila Times. https://www.manilatimes.net/2022/05/12/business/agribusiness/abonong-swak-campaign-launched.

HERMANS C, HAMMOND JP, WHITE PJ, VERBRUGGEN N. 2006. How do plants respond to nutrient shortage by biomass application?. Trends Plant Sci. 11(12):610–617. doi:10.1016/j.tplants.2006.10.007.

How2statsbook. 2019. V9.9 – three-way (2 x 2 x 2) between-subjects ANOVA in SPSS. https://www.youtube.com/watch?v=AHRJSY1HpLU.

IIJIMA M, KATO J, TANIGUCHI A. 2007. Combined soil physical stress of soil drying, anaerobiosis and mechanical impedance to seedling root growth of four crop species. Plant Prod Sci. 10(4):451–459. doi:10.1626/pps.10.451.

ISLAM SMM, GAIHRE YK, BISWAS JC, JAHAN MS, SINGH U, ADHIKARY SK, ABDUS SATTER M, SALEQUE MA. 2018. Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: fate of nitrogen and grain yield. Agric Water Manage. 196:144–153. doi:10.1016/j.agwat.2017.11.002.

JIA Y, YANG X, FENG Y, JILANI G. 2008. Differential response of root morphology to potassium deficient stress among rice genotypes varying in potassium efficiency. J Zhenjiang Univ Sci B. 9(5):427–434. doi:10.1631/jzus.B0710636.

JIANG S, DU B, WU Q, ZHANG H, ZHU J. 2023. Increasing pit-planting density of rice varieties with different panicle types to improve sink characteristics and rice yield under alternate wetting and drying irrigation. Food Energ Secur. 12(1):e335. doi:10.1002/fes3.335.

KAR S, VARADE SB, GHILDYAL BP. 1979. Pore size distribution and root growth relations of rice in artificially synthesized soils. Soil Sci. 128(6):364–368. https://journals.lww.com/soilsci/abstract/1979/12000/pore_size_distribution_and_root_growth_relations.8.aspx.

MADHAVI P, JAYASREE G, ANJAIAH T, PRATIBHA G, HUSSAIN SA. 2022. Water management practices and nitrogen sources effects on N-mineralization and use efficiency in Rabi paddy (*Oryza sativa* L.) in Southern Telangana. Int J Environ Clim Change. 12(1):134–140. doi:10.9734/ijecc/2022/v12i130832.

MAGAHUD JC, DALUMPINES SLP, LINCUNA AE JR., ESTOY GF JR. 2019. Growth of rice, PSB Rc 82, and status of nutrients in lowland Agusan soil under alternate wetting and drying and minus-one-element conditions. Philipp Sci Lett. 12(2):107–121. https://www.researchgate.net/publication/336106761_Growth_of_rice_PSB_Rc_82_and_status_of_nutrients_in_lowland_Agusan_soil_under_alternate_wetting_and_drying_and_minus-one-element_conditions.

MAGAHUD JC, PADIOS PAB. 2022. Yield-contributing factors in lowland irrigated rice as affected by variety, water management and fertilizer rate in Agusan soil. Philipp J Sci. 151(3):913–935. https://philjournalsci.dost.gov.ph/images/pdf/pjs_pdf/vol151no3/yield_contributing_factors_in_lowland_irrigatd_rice_affected_by_water_mngt_and_fertilizer_rate_.pdf.

MURTHY KMD, RAO AU, VIJAY D, SRIDHAR TV. 2015. Effect of levels of nitrogen, phosphorus and potassium on performance of rice. Indian J Agric Res. 49(1): 83–87. https://arccarticles.s3.amazonaws.com/webArticle/articles/A4037.pdf.

ORTIZ AA, ESTOY GF JR. 2013. Enhancement of beneficial organisms through soil amendment applications in Caraga region. Philippine Rice R&D Highlights 2012. https://www.philrice.gov.ph/2012-rd-highlights/.

[PCAARRD] Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development. 1980. Standards methods of analysis for soil, plant tissue, water and fertilizer. Laguna, Philippines: PCAARRD. 194 p.

[PHILRICE] Philippine Rice Research Institute. 2007. PalayCheck system for irrigated lowland rice. Science City of Muñoz, Philippines: PhilRice. 91 p.

[PHILRICE] Philippine Rice Research Institute. 2011. PSB and NSIC varieties 2010. In: FAQS on Philippine Seed Board (PSB)/NSIC Rice Varieties. Science City of Muñoz, Philippines: PhilRice. https://www.pinoyrice.com/rice-varieties/.

[PHILRICE-SED] Philippine Rice Research Institute–Socioeconomics Division. 2024. Estimated production, area harvested and yield per hectare (PAY). PalayStat. https://palaystat.philrice.gov.ph/statistics/retrieve/table/1.

ROLLON RJC, GOLIS JM, SALAS E. 2021. Impacts of soil nutrient management practices on soil fertility, nutrient uptake, rice (*Oryza sativa* L.) productivity, and profitability. J Appl Biol Biotechnol. 9(2):75–84. doi:10.7324/JABB.2021.9207.

SATUITO M, VALENZUELA MA. 2022. Masbate, Samar, Laguna farmers to try Abonong Swak. Department of Agriculture-Philippine Rice Research Institute. https://www.philrice.gov.ph/masbate-samar-laguna-farmers-to-try-abonong-swak/.

SHEKHAR S, MAILAPALLI DR, RAGHUWANSHI NS. 2021. Simulating nitrogen transport in paddy crop irrigated with alternate wetting and drying practice. Paddy Water Environ. 19:499–513. doi:10.1007/s10333-021-00850-x.

SOBREVILLA RL, MABAYAG CA. 2013a. Determination of nutrient use efficiency and yield potential of rice varieties/promising lines adapted to Caraga Region. Philippine Rice R&D Highlights 2012. https://www.philrice.gov.ph/2012-rd-highlights/.

SOBREVILLA RL, MABAYAG CA. 2013b. Improving rice yield in Caraga Region: the effect of plant spacing and fertilizer application on the nutrient-use efficiency and yield of selected varieties under low solar radiation. Philippine Rice R&D Highlights 2012. https://www.philrice.gov.ph/2012-rd-highlights/.

SOLEDAD MF JR, VARQUEZ FL. 2013a. Evaluation of INM practices for sustainable yield of rainfed lowland rice in Mindanao. Philippine Rice R&D Highlights 2012. https://www.philrice.gov.ph/2012-rd-highlights/.

SOLEDAD MF JR, VARQUEZ FL. 2013b. Identification of soil fertility constraints to yield of lowland rice in saline-prone areas in Mindanao. Philippine Rice R&D Highlights 2012. https://www.philrice.gov.ph/2012-rd-highlights/.

SYS C, VAN RANST E, DEBAVEYE J, BEERNAERT F. 1993. Land evaluation. Part III: crop requirements. Brussels (Belgium): Agricultural Publications, General Administration for Development Cooperation. 199 p.

TROZA M, SUTACIO A, POLINAR A, ROLLON RJC. 2021. Soil nutrient status and yield of rice under organic and inorganic inputs. J Appl Biol Biotechnol. 9(6):181–188. doi:10.7324/JABB.2021.96023.

VERHOEVEN E, DECOCK C, BARTHEL M, BERTORA C, SACCO D, ROMANI M, SLEUTEL S, SIX J. 2018. Nitrification and coupled nitrification-denitrification at shallow depths are responsible for early season N2O emissions under alternate wetting and drying management in an Italian rice paddy system. Soil Biol Biochem. 120:58–69. doi:10.1016/j.soilbio.2018.01.032.

WITT C, DOBERMANN A. 2002. A site-specific nutrient management approach for irrigated, lowland rice in Asia. Better Crops Int. 16(1):20–24. http://www.ipni.net/publication/bci.nsf/0/870A90403A1BDBB585257BBA0065CC62/$FILE/Better%20Crops%20International%202002-1%20p20.pdf.

XU X, XIE J, HOU Y, HE P, PAMPOLINO MF, ZHAO S, QIU S, JOHNSTON AM, ZHOU W. 2015. Estimating nutrient uptake requirements for rice in China. Field Crops Res. 180:37–45. doi:10.1016/j.fcr.2015.05.008.

YE T, ZHANG J, LI J, LU J, REN T, CONG R, LU Z, LI X. 2021. Nitrogen/potassium interactions increase rice yield by improving canopy performance. Food Energ Secur. 10(3):e295. doi:10.1002/fes3.295.